Harvard-Smithsonian Center for Astrophysics

Precision Astronomy Group

MEMORANDUM

To: K. J. Johnston
From: J.D. Phillips
Subject: Draft report of the Technical Subcommittee on Filters vs. Gating
Date: 4/20/99

This draft reports on the work to date of the Technical Subcommittee on Filters vs. Gating, whose members are J. Geary, M. Germain, F. Harris, D. Monet, R. Vassar, and myself (chair).

The FAME CCD's would saturate for stars brighter than a magnitude that depends on where in the pixel the star falls, and on the precession-induced smearing, but is in the range V=7 to 9.4, using nominal values from the current design. Among these stars are almost all Cepheid and RR Lyrae variables within 1 kpc, which are critical to the scientific objectives.

This memo discusses two ways of obtaining measurements of stars of V>~9, gating the clock of the CCD on which a bright star falls (Start-Stop Technology, SST), and placing neutral density filters in front of several CCD's. It also mentions two methods raised in the past which we do not foresee considering further.

The conclusion is that a sensible baseline for FAME is to use SST, with plans to investigate systematic error experimentally, and with neutral filters as a fallback that may offer reduced systematic error, but yields substantially lower precision.

Start-Stop Technology

Description

The clock for a CCD chip that is about to see a bright star is stopped just before the star comes onto the imaging area. This creates a trailed image at the beginning of the chip (Fig. 1a). Once the entire PSF is on the imaging area, the clock is restarted (with the clock lines in the same state as when it was stopped). It runs for an integration time t_i, which is a multiple of the row-shift interval, creating a normal Time-Delay Integration (TDI) image. We choose t_i to be short enough that the image does not saturate. The clock is halted again (Fig. 1c), creating a trailed image on the other side of the first TDI image. This process is repeated, resulting in a series of trailed images connecting TDI images. When the star nears the serial register, clocking is halted one last time, creating one final trailed image "ahead" of the last real image (Fig. 1e). The clock

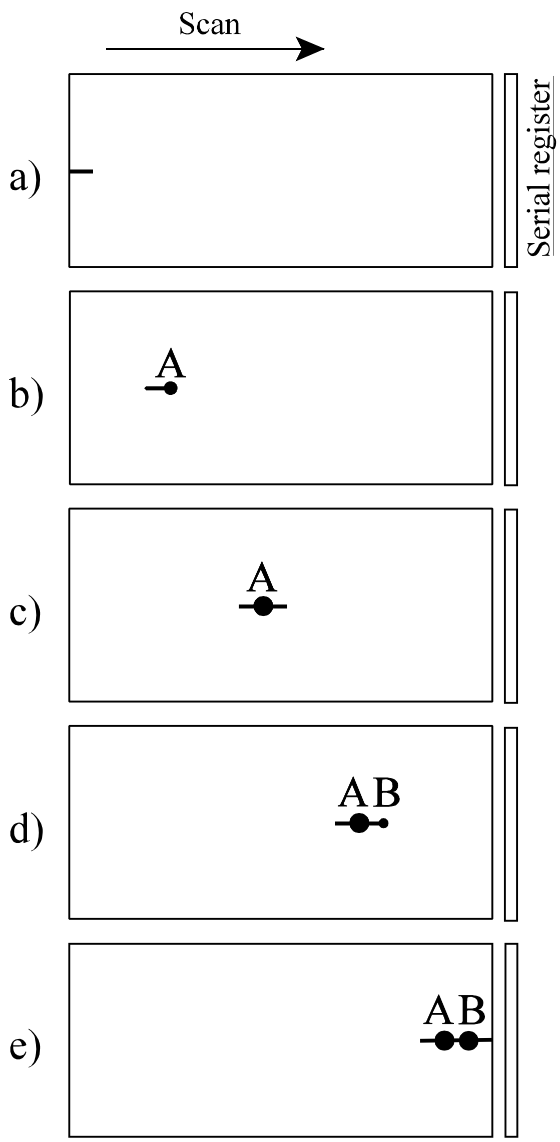

Figure 1. Image buildup with clock gating. Five successive states of the same CCD are shown, top to bottom. a) The bright star enters the chip, with the clock gated off. b) Clocking has been restarted, and image A is accumulating. c) Image A approaches full-well, and the clock is again gated off. d) Clocking has been restarted, and image B is accumulating. e) Image B approaches full-well, and the star approaches the edge of the chip. Clocking is halted, and the star crosses the edge of the chip leaving a trail. Clocking is restarted, and left on until the next bright star arrives. Then images B, then A, are read out.

is restarted when the entire PSF has left the photosensitive part of the chip. The images are read out, with the last one accumulated being read out first. The small readout window (e.g., 10 pixels in the scan direction by 4 co-added pixels in cross-scan) is replaced by a "ribbon of data" of greater extent in the scan direction.

Brighter stars would require a shorter t_i, so the clock would stop more often.

The clock is stopped by holding the clock lines at a latch. To halt only the chip having a bright star requires a separate clock driver for each chip. It may significantly reduce the cost of the electronics if several CCD's are driven by the same driver chip. If this is done, it would be necessary to halt clocking on all CCD's driven in parallel with the one having the bright star.

This would entail only a modest compromise of the data, particularly if the groups of chips driven by a single driver do not form a repeating pattern.

It may be convenient to have a binary sequence of stoppages, 1, 2, 4, 8, etc., up to about 512 stoppages. The limit to the number is that there must be several pixels having trailed images between each pair of TDI images.

Images of fainter stars that happened to be on the chip when the clock is halted would not be lost. They would be strung out into a series of images in a manner similar to the bright star, but without the symmetrically arranged trails. Modelling would permit using those images, although greater systematic error is possible. Further, the modelling would yield valuable information about biases introduced by the starts and stops. To get measurements of faint stars near bright ones, at least to get a sample of unbiased measurements for comparison, the start-stop technique might be used only for some passages of bright stars. Only those faint stars falling within a few arcsec of bright stars would be unobservable.

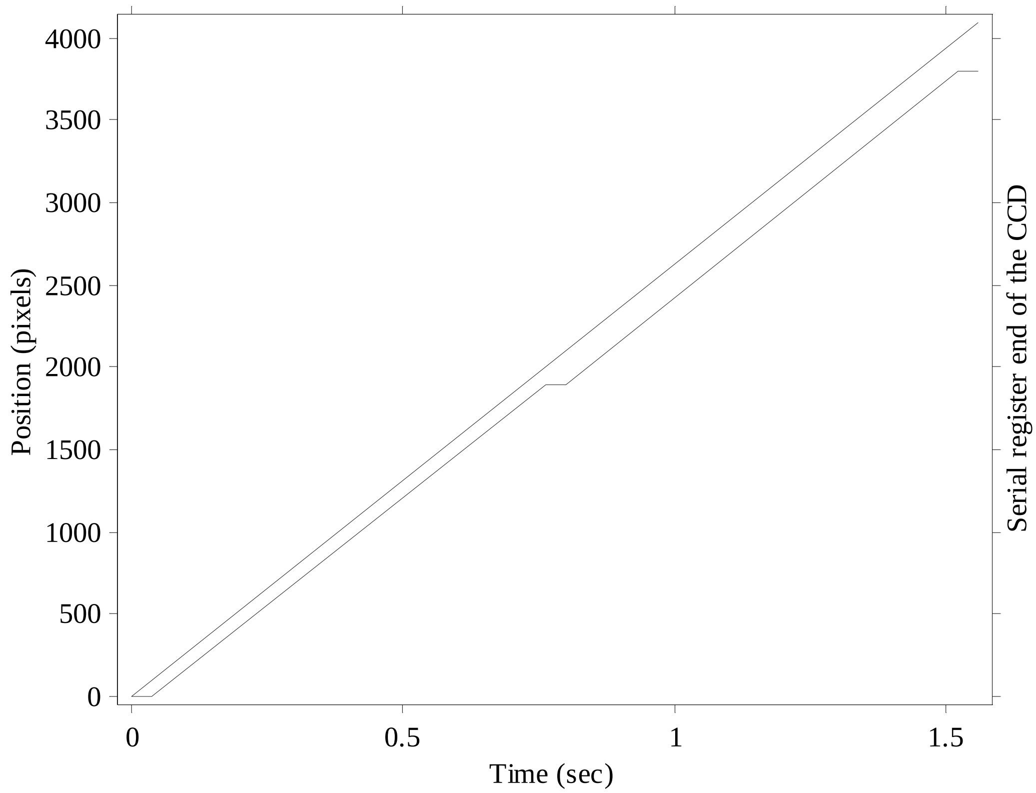

Figure 2. Position on the CCD vs. time corresponding to the images in Fig. 1. Straight diagonal line shows the position of the star, and line with steps is charge packet position in bright star mode, with 2 start-stop cycles of the clock. (The length of time that the clock is stopped is exaggerated for clarity.) At the right-hand side of the figure, the star moves off the edge of the chip. Normal clocking can then resume. Two charge packets, separated by the lengths of time that the clock was stopped, will presently be read out.

Two bright stars falling within one chip length (along the scan direction) of one another will require bright-star clocking at the same time. There are about 100,000 stars of V<9 [Allen 1976], or 2.5 per sq. deg. In the 15 m focal length design, one 4096 x 2048 pixel CCD having 15 μm square pixels subtends 0.117 × 0.234 deg., or 0.027 sq. deg. Therefore this happens for about 1/7 of bright stars. (This number may be reduced substantially if observations of stars of V>~8 that do not saturate due to precession smearing are made with ordinary faint-star clocking.) The clocking program in this case could stop and start the clock the number of times appropriate to the brighter star when it was on the chip, but continue to stop and start the clock for an extended period that covers the time that either star is on the chip. The measurements of the fainter star would not be optimized with respect to read noise, but the images are likely to be above the transition magnitude for read noise anyway, so this is not a disadvantage. The star for which the clock gating program was not optimized would not have all real images surrounded by trailed images, and the modelling of the trails might entail bias.

Table 1 *Start-stop technology advantages.*

Overlap between bright and faint	<<Calculate magnitudes of overlap for both techniques.>>
Bright stars	
Information	20/3 x 40 = 267. σ lower than for filters by a factor 16.
Color information for V<~7.5.	Available. Needed for starting procedure now in use by Chandler and Reasenberg. N.B.: High precision measurements of bright stars provide one probe of systematic error. N.B.: even without SST, photometry is available ~1½ mags brighter than saturation in faint-star astrometry chips bec. filters have 1/4 bandwidth.
Very bright stars (V<5)	Can be measured, perhaps to V~1. Brighter stars have more TDI images (but not more photons per image), so greater precision, but also brighter trailed images, so increased possibility of systematic error.
Faint stars	
Information	20/17 times more; 8% reduction of σ.

Start-stop technology disadvantages.

The images having multiple TDI images connected by trailed images must be modelled. There may be CCD effects that must be measured experimentally to do this, and tests must be done to verify that the CCD behaves as expected.

Traps in the CCD hold charge, removing it preferentially from the leading edge of an image and in some cases restoring it to the trailing edge. A trap with a hold time shorter than the time it last saw a charge packet go past will not accept charge from the current packet. Breaking the column up into multiple integrations means that a trap will have a different effect on different images. A separate error model will be required for each segment of each different segmenting of the CCD (i.e., for each of the N_{SS} segments, for each different value of N_{SS} of Table 2). Traps hold up to a few 100 electrons: the specification sheet for the EEV 44-82 BI, grade 1, calls for <30 traps holding more than 200 e. A typical bright-star image will have a peak value of more than half of full-well, about 5×10^4 e. Therefore the shift is of order 1/200 pixel, somewhat greater than the single-measurement precision. The shift must be modelled, and the modelling can probably not be entirely successful on an individual basis, since charge transfer by a trap depends on its illumination history. Also, the CCD temperature may vary enough to affect the trap's behavior, and radiation-induced traps will appear during the mission. The time they were created will need to be modelled. It may be that radiation-induced traps hold less charge. <<F. Harris is going to ask Janesick or Janesick's collaborators about this.>>

Measurements of faint stars within ~1/4 sq. deg. of a bright star may be affected by clock gating. The extent of the effect depends on the accuracy with which the images between trails can be modelled. The operations plan can be adjusted to sacrifice some bright star observations in favor of some observations of fainter stars. Stars at the transition magnitude, at which read noise increases σ by a factor $\sqrt{2}$, and fainter (V<~15), will suffer additional read noise due to being spread into multiple images by starts and stops.

Traps. Filling is illumination-dependent.

Neutral filter

Description

Several CCD's, nominally 3, are designated for bright star observations only. These are provided with filters having an attenuation sufficient to bring the brightest star to be observed within the magnitude range of the CCD. The filters should be neutral density (ND), i.e., this attenuation should be roughly independent of wavelength. Nominally, a 5th magnitude star will be reduced to 9th, requiring attenuation by a factor of 40.

Neutral filter advantages.

• Simplicity. <<Elaborate on this.>>

• Traps in the CCD's need only one model, for stars travelling the entire length of the column.

Neutral filter disadvantages.

• Requires one of two options for photometry for V<7.5 (approx.: the onset of saturation in astrometry chips is V~9, but photometry chips see only ~1/4 of the passband.):

a) Two of the four photometry chips are dedicated to bright stars, with ND filters in addition to the color filters. This removes the planned redundancy between photometry chips, and reduces the accuracy of the photometry, and the frequency of photometric observations (N.B.: observations in all four filter bands are required).

b) Additional photometry chips, with ND filters. Space can probably be found in the focal plane for these chips, but their cost would be significant. To have the same temporal coverage as for the faint stars, an additional four photometry chips would be needed.

Bright-star photometry cannot be obtained from the ground. There are 20-30,000 stars involved. Ideally, photometry is required at the epoch of each visit, although this will not be available for all visits whose photometry is obtained on orbit in the ordinary photometry chips, even if all four are available for faint stars. All stars more than 45° from the Sun will be observed astrometrically, so will need photometry. This would require telescopes at many latitudes.

• ND filters might be deposited on a window that was required for other reasons anyway, for instance protecting the CCD's from contamination or limiting the passband. They might also require glass in the path that would otherwise not be required. Glass is to be avoided if possible, because it would cause a wavelength-dependent, field-dependent skew of the PSF; thermal shift; and if not used on all chips, the chips with windows would have to be recessed to be in focus, and would have different spherical aberration.

Table 2. Precision achievable with SST and filter approaches. Values for precision are based on the design with 7.5 m focal length. (An update to the current 15 m focal length is planned soon, JDP, 4/20/99.) N_{SS} is the number of starts and stops at magnitude V. Question marks indicate that those measurements may not be feasible with the clock gating method. Number of stars is calculated from Allen, 1976.
* includes systematic error and read noise.

V mag	$\sigma_{mission}^{*}$		N_{SS}	Total # of stars, approx., in [V-0.5, V+0.5]
	w/ 40 x filters on 3 chips	w/ SS tech. (20 chips)		
1	–	10	?	16
2	–	10	1024 ?	58
3	–	10	256	200
4	–	10	128	630
5	29	10	64	1900
6	44	11	16	5500
7	68	11	8	16000
8	18	12	4	45000
9	15	15	1	130000

Third, narrow, aperture
Advanced 8/98 by RDR and JDP, currently tabled.

Wings of PSF
Advanced in early 1997 by RDR and JDP, currently tabled.

Reference

Allen, *Astrophysical Quantities*, Athlone Press, London, 1976, p. 244.